

PI, PID and Fuzzy logic controller for Reactive Power and Harmonic Compensation

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Abstract— This article describes the proportional integral (PI), proportional integral derivative (PID) and fuzzy logic controller (FLC) based three phase shunt active power line conditioners (APLC) for the power-quality improvement such as reactive power and harmonic current compensation generated due to nonlinear loads. PI, PID controller requires precise linear mathematical model and FLC needs linguistic description of the system. The controller is capable of controlling dc capacitor voltage and generating reference source currents. Hysteresis current controller is used for current control in PWM voltage source inverter. Extensive simulation studies under transient and steady states are conducted, the simulation result analysis reveal that the APLC performs perfectly in conjunction with PI, PID and FLC. A comparative assessment of the three different controllers is brought out.

Index Terms—Proportional Integral (PI) controller, Proportional Integral Derivative (PID) controller Fuzzy logic controller (FLC), Hysteresis current controller (HCC), Active power line conditioners (APLC).

I. INTRODUCTION

AC power supply feeds different kind of linear and non-linear loads in utilities and industrial applications. The non-linear loads produce harmonics. The harmonic and reactive power cause poor power factor and distort the supply voltage at the common coupling point or customer service point [1-3]. Passive L-C filters are used to compensate the lagging power factor of the reactive load, but there are drawbacks such as resonance, large size, weight, etc., the alternative solution, are an active power line conditioner (APLC) that provides an effective solution for harmonics elimination and reactive power compensation. The controller is the most important part of the APLC and currently lot of research is being conducted in this area. PI and PID controllers have been used to extract the fundamental component of the load current(s) and simultaneously control dc capacitor voltage of the shunt APLC [1-2]. Recently, fuzzy logic controllers (FLC) are used in power electronic system [3-5] as it can handle nonlinearity, and it is more robust than conventional nonlinear controllers.

This paper explores the potential and feasibility of PI, PID and FLC schemes that are suitable for extracting the fundamental component of the load current(s) and simultaneously controlling dc capacitor voltage of the shunt APLC. The performance of APLC with different controllers are evaluated through computer simulations

under both steady state and transient conditions. The operation of APLC is demonstrated in details. The methods of extracting reference current(s) and dc capacitor voltage is also presented. The results are also presented that validates the concept and a comparative assessment is done.

II. DESIGN OF SHUNT APLC

The active power line conditioner comprises of six power transistors six power diodes, a dc capacitor, three filter inductor. Reduction of current harmonics is achieved by injecting equal but opposite current harmonic components at the point of common coupling (PCC), this facilitates improving the power quality on the connected power system. The APLC additionally supplies the reactive current component of the load current. The block diagram of APLC is shown in fig 1. The output voltage of the inverter is controlled with respect to the voltage at the point of common coupling. The design of the DC side capacitor is based on the principle of instantaneous power flow. The selection of C_{DC} can be governed by reducing the voltage ripple.

The instantaneous current can be written as [4]

$$i_s(t) = i_L(t) - i_c(t) \quad (1)$$

Source voltage is given by

$$v_s(t) = V_m \sin \omega t \quad (2)$$

If a nonlinear load is applied, then the load current will have a fundamental component and harmonic components, which can be represented as

$$\begin{aligned} i_L(t) &= \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n) \\ &= I_1 \sin(\omega t + \Phi_1) + \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \end{aligned} \quad (3)$$

The instantaneous load power can be given as

$$\begin{aligned} p_L(t) &= i_s(t) * v_s(t) \\ &= V_m \sin^2 \omega t * \cos \phi_1 + V_m I_1 \sin \omega t * \cos \omega t * \sin \phi_1 \\ &\quad + V_m \sin \omega t * \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \\ &= p_f(t) + p_r(t) + p_h(t) \end{aligned} \quad (4)$$

From the equation the real (fundamental) power drawn by the load is

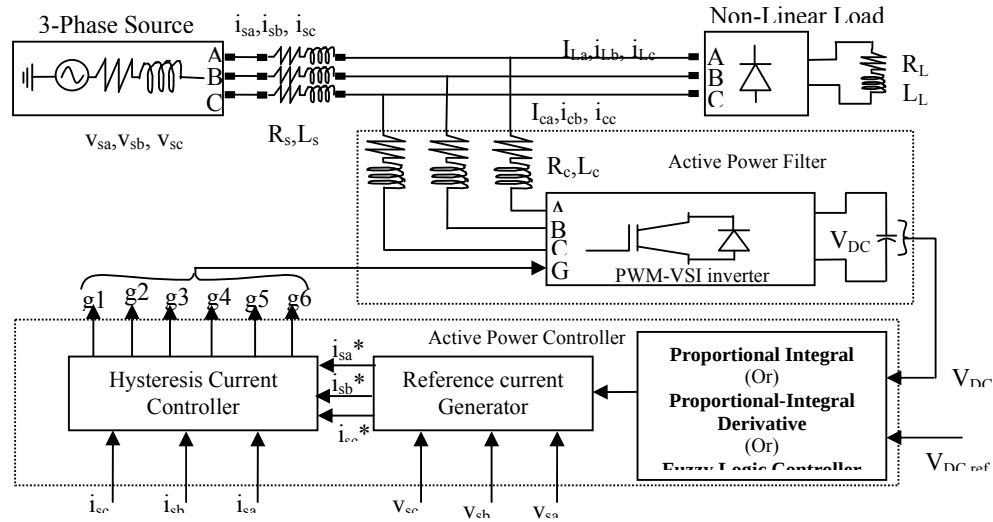


Fig 1 Block diagram of the Proposed APLC based on Fuzzy logic controller or Proportional-Integral controller

$$p_f(t) = V_m I_1 \sin^2 \omega t \cos \phi_1 = v_s(t) * i_s(t) \quad (5)$$

From this equation the source current supplied by the source, after compensation is

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 \cos \phi_1 \sin \omega t = I_{sm} \sin \omega t \quad (6)$$

where,

$$I_{sm} = I_1 \cos \phi_1 \quad (7)$$

The total peak current supplied by the source is

$$I_{sp} = I_{sm} + I_{sl} \quad (8)$$

If the active filter provides the total reactive and harmonic power, then $i_s(t)$ will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensation current:

$$i_c(t) = i_L(t) - i_s(t) \quad (9)$$

The desired source currents, after compensation, can be given

$$i_{sa}^* = I_{sp} \sin \omega t \quad (10)$$

$$i_{sb}^* = I_{sp} \sin(\omega t - 120^\circ) \quad (11)$$

$$i_{sc}^* = I_{sp} \sin(\omega t + 120^\circ) \quad (12)$$

Where $I_{sp} = I_{sm} + I_{sl}$ is the amplitude of the desired source current.

A. Proportional Integral (PI) Controller:

Figure 2 shows the block diagram of the proposed PI control scheme of an APLC. The DC side capacitor voltage is sensed and then compared with a reference value. The obtained error $e = V_{dc,ref} - V_{dc}$ at the n^{th} sampling instant is used as input for PI controller. PI controller used to control the DC-bus voltage.

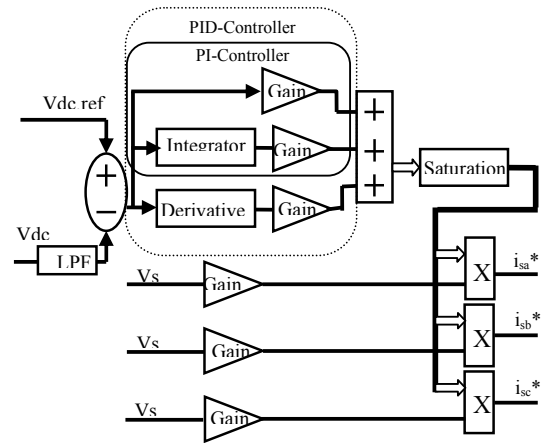


Fig 2 PI and PID- controller for reference current generator

Its transfer function can be represented as

$$H(s) = K_p + \frac{K_I}{s} \quad (13)$$

where, K_p is the proportional constant that determines the dynamic response of the DC-bus voltage control and K_I is the integration constant that determines its settling time. PI controller to eliminate the steady state error in dc voltage. The proportional gain [$K_p = 0.3$] and integral gain [$K_I = 9$] are set such way that V_{dc} across capacitor is nearly equal to the reference value of V_{dc} .

B. Proportional Integral Derivative (PID) Controller:

The PID controller works on the principle of the PI controller (refer fig 2), its control gain is a linear combination of the error itself representing the present, the integral of the error representing the past and the derivative of the error representing the future/trend.

$$H(s) = K_p + \frac{K_I}{s} + K_D(s) \quad (14)$$

The controller is tuned with proper gain parameters [$K_p=0.7, K_I=23, K_D=0.01$].

C. Fuzzy Logic Controller (FLC):

Fuzzy logic control is derived from fuzzy set theory, the transition between membership and non-membership can be gradual. Therefore, boundaries of fuzzy sets can be vague and ambiguous, making it useful for approximate systems [4-5]. In fig.1 shows the APLC compensation system with fuzzy control scheme. In order to implement the control algorithm of a shunt active power line conditioner in a closed loop, the dc capacitor voltage V_{DC} is sensed and then compared with the reference value $V_{DC,ref}$.

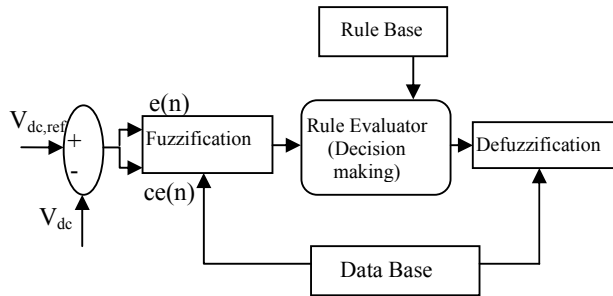


Fig 3 Fuzzy logic controller

Table 1 Rule base table

$\frac{ce(n)}{e(n)}$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

In case of a fuzzy logic control scheme, the error ($e = V_{DC,ref} - V_{DC}$) and integration of error signal ($\int e$) are used as inputs for fuzzy processing shown in fig 3. The output of the fuzzy controller after a limit is considered as the magnitude of peak reference current I_{max} . The switching signals for the PWM inverter are obtained by comparing the actual source currents (i_{sa}, i_{sb}, i_{sc}) with the reference current templates ($i_{sa}^*, i_{sb}^*, i_{sc}^*$) in the hysteresis current controller. The output pulses are then given to the switching devices of the PWM converter. The rules used in this paper are shown in table 1.

D. Hysteresis Band Current Control:

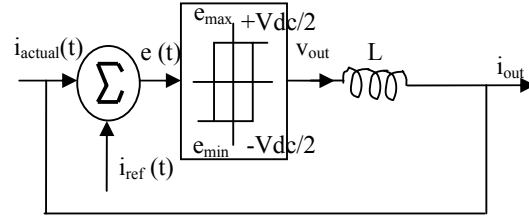


Fig 4 Block diagram of hysteresis current controller

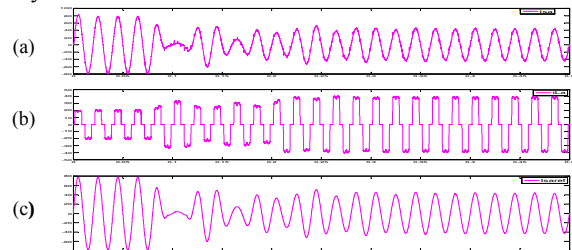
A hysteresis current controller (Fig. 4) is implemented to control the switches in the inverter [6-8] to control the current within the inverter.

III. SIMULATION RESULT AND ANALYSIS

The results of the proposed PI, PID and fuzzy logic controlled shunt APLC is investigated using SIMULINK/MATLAB. The system parameters values are; source voltage (V_s) is 230 Vrms, System frequency (f) is 50 Hz, Source impedance of R_s, L_s is 1 Ω ; 0.1mH respectively, Filter impedance of R_c, L_c is 1 Ω ; 2.7 mH, Load impedance of R_L, L_L of diode rectifier RL load in Steady state: 20 Ω ; 200 mH and Transient: 10 Ω ; 100 mH respectively, DC link capacitance (C_{DC}) is 1600 μ F, Reference Voltage (V_{DC}) is 400 V and Power devices used are IGBT/Diode.

Case 1: Proportional Integral controller:

PI-controlled APLC system comprises of a three-phase source, a nonlinear load (six pulse diode rectifier bridge feeding an RL load) and a PWM voltage source inverter with a dc capacitor input. The simulation time $T=0$ to $T=0.5s$ with diode rectifier and RL load parameter values of 20 ohms and 200 mH respectively. The source current after compensation is presented in fig. 5 (a) that indicates the current becomes sinusoidal. The load current is shown in (b) for a particular phase (phase a). The actual reference currents for phase (a) are shown in fig. 5(c). This wave is obtained from our proposed PI controller. The APLC supplies the compensating current that is shown in Fig. 5(d). The current after compensation is as shown in (a) which would have taken a shape as shown in (b) without APLC. It is clearly visible that this waveform is sinusoidal with some high frequency ripples. We have additionally achieved power factor correction as shown in Fig. 5(e), phase (a) voltage and current are in phase. The time domain response of the PI controller is shown in Fig. 5(f) that clearly indicates the controller output settles after a few cycles.



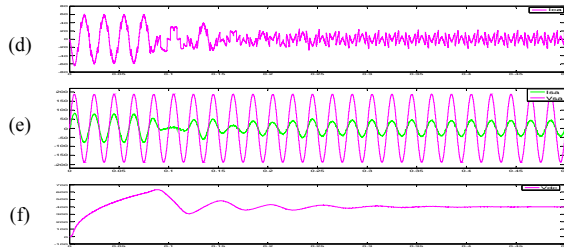


Fig.5 Simulation results for PI-controlled three-phase APLC under the steady state condition (a) Source current after APLC, (b) Load currents, (c)Reference currents by the Proportional-integral algorithm, (d) Compensation current by APLC, (e) source voltage per current for unity power factor and (f) DC capacitor voltage

The active power P and reactive power Q associated with a periodic voltage-current pair that can contain harmonics. P and Q are calculated by averaging the voltage-current product with a running average window over one cycle of the fundamental frequency (refer fig 6).

$$P = \frac{1}{T} \int_{t-T}^t V(\omega t) \times I(\omega t) dt \quad (15)$$

$$Q = \frac{1}{T} \int_{t-T}^t v(\omega t) \times i(\omega t - \pi/2) dt \quad (16)$$

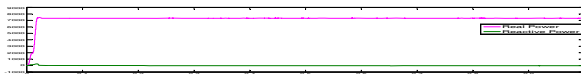


Fig 6 Active and Reactive power at diode rectifier RL load under the steady state condition (P=7.34 KW, Q=0.04 KW)

Total Harmonic distortion (THD) is measured of the APLC in the PI controller, shown in fig 7.

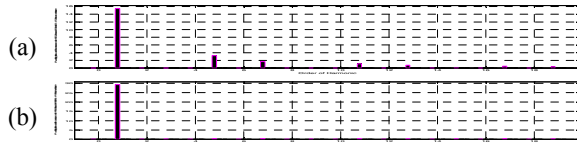


Fig 7 PI-controlled under the steady state (a) FFT analysis of Source current without APLC (THD=25.58%) (b) with APLC(THD=1.98%).

Case 2: Proportional Integral Derivative controller:

ID controlled simulation waveforms are verified similarly PI-controller, PID controller waveform presented in figures 8, 9 and 10.

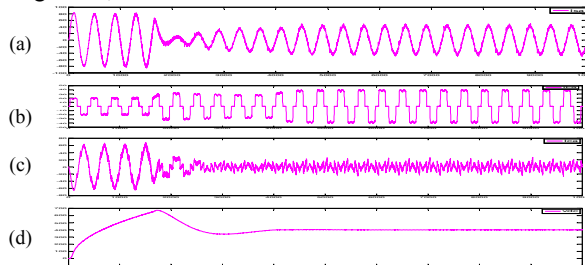


Fig.8 Simulation results for PID controlled 3-phase APLC under the steady state condition (a) Source current after APLC, (b) Load currents, (c) Compensation current by APLC, and (d) DC capacitor voltage

The real and reactive power measured using PID controller, shown in fig 9.

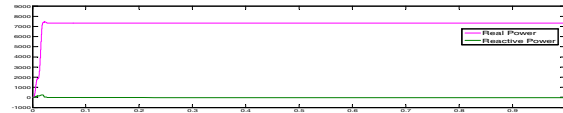


Fig 9 Active and Reactive power at diode rectifier RL load under the steady state condition (P=7.34 KW, Q=0.034 KW)

Total Harmonic distortion measurement (THD) of the APLC in the transient condition by proportional-integral derivative controller, shown in fig 10.

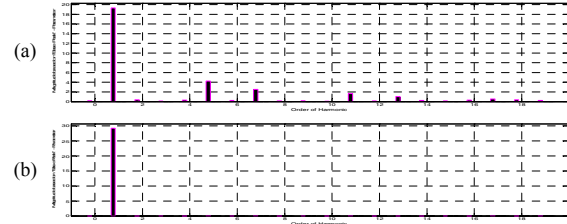


Fig 10 PID-controlled under the Transient condition (a) FFT analysis of Source current without APLC(THD=24.96%) (b) with APLC(THD=2.96%).

Case 3: Fuzzy logic controller:

Simulation time T=0 to T=0.5s with load of rectifier with RL parameter values of 20 ohms and 200mH respectively in the steady state and the load with R L value of 10 ohms and 100 mH under transient condition. The simulated waveforms are presented in figures 11, 12 and 13.

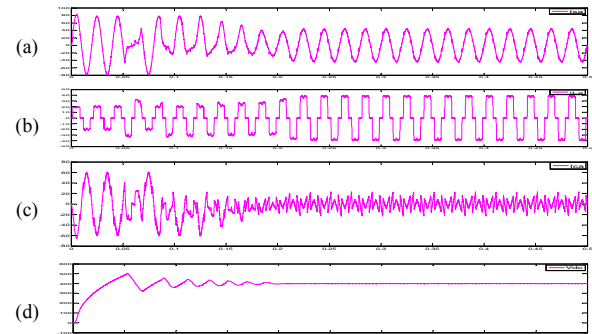


Fig.11 Simulation results for Fuzzy Logic Controlled 3-phase APLC under the steady state condition (a) Source current after APLC, (b) Load currents, (c) Compensation current by APLC, and (d) DC capacitor voltage

The summarized DC voltage settling time compared PI, PID and Fuzzy logic controller, shown in table 2

Table 2 comparison of PI, PID and FLC for DC voltage settling time

Diode rectifier RL load	V _{DC} settling time in seconds		
	PI controller	PID controller	Fuzzy logic controller
Steady State	0.37s	0.26s	0.22s
Transient	0.39s	0.28s	0.23s

The real and reactive power measured using fuzzy logic controller, shown in fig 12.

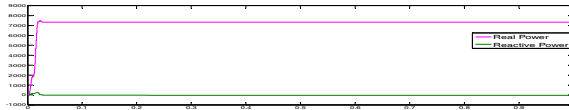


Fig 12 Active and Reactive power at diode rectifier RL load under the steady state condition ($P=7.33$ KW, $Q=0.04$ KW)

The summarized Real (P) and Reactive (Q) power calculation compared with PI, PID and Fuzzy logic controller, shown in table 3.

Table 3 comparison of PI, PID and FLC for Real and Reactive power

Controller	Condition	Real (P) and Reactive (Q) power measurement	
		Without APLC	With APLC
PI	Steady state	$P=3.90$ KW $Q=0.12$ KW	$P=7.34$ KW $Q=0.04$ KW
	Transient	$P=4.85$ KW $Q=0.16$ KW	$P=7.34$ KW $Q=0.07$ KW
PID	Steady state	$P=3.90$ KW $Q=0.12$ KW	$P=7.34$ KW $Q=0.03$ KW
	Transient	$P=4.85$ KW $Q=0.16$ KW	$P=7.34$ KW $Q=0.07$ KW
Fuzzy logic	Steady state	$P=3.91$ KW $Q=0.13$ KW	$P=7.33$ KW $Q=0.04$ KW
	Transient	$P=4.83$ KW $Q=0.17$ KW	$P=7.35$ KW $Q=0.08$ KW

Total Harmonic distortion measurement of the APLC in the fuzzy logic controller, shown in fig 13.

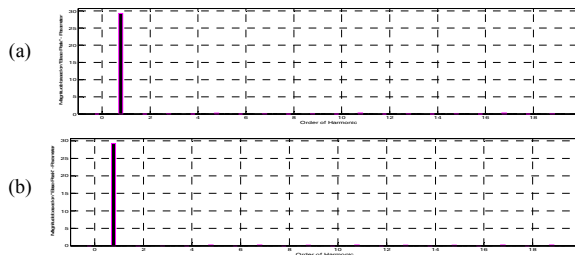


Fig 13 Fuzzy logic controlled FFT analysis of Source current with APLC under the (a) steady state (THD=1.98%) (b) transient (THD=2.98%)

The summarized Total harmonic distortion (THD) compared PI, PID and Fuzzy logic controllers, under steady state and transient conditions, shown in table 4.

Table 4 THD comparison of PI, PID and FLC Techniques

Diode rectifier RL load	Source Current(I_s) without APLC	Source Current(I_s) with APLC		
		PI	PID	Fuzzy logic
Steady State	25.258%	1.98%	1.82%	1.98%
Transient	24.96%	2.96%	2.96%	2.98%

The obtained result shows small variation in steady state and transient conditions. FFT analysis of the active filter brings the THD of the source current into compliance with IEEE-519 standards.

CONCLUSIONS

PI, PID and fuzzy logic controllers are implemented for three phase shunt active power line conditioner to obtain dc capacitor voltage and the reference currents. This facilitates to improve the power quality parameters such as reactive power and harmonic compensation due to nonlinear load. The performance of a PI, PID and fuzzy logic controlled APLC is verified and compared under steady state and transient in various disciplines. The fuzzy logic controller reduces ripples in the dc capacitor voltage and needs less settling time compared to PI and PID-controller. The THD of the source current after compensation is less than 5% in case of all the controllers, the harmonic limit imposed by the IEEE-519 standard. Apparently it seems that the fuzzy logic controller is an effective candidate for active power line conditioner to solve power quality issues as this would also facilitate easy implementation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge to Ministry of Communication and Information Technology, Govt. of India for the financial support.

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